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by

H. H. Lamb

(Meteorological Office)

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

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Summary

The data available, which are admittedly and as yet unavoidably scanty, suggest that the southern hemisphere westerlies carry much more momentum than their northern counterparts, possibly by as much as a factor of nearly two over the year as a whole. In the northern summer-southern winter the factor is approximately four. The system appears to be the most energetic limb of the atmospheric circulation, and it may be useful to regard it as the "flywheel" and a sort of (partial) "governor".

Preliminary survey at the 500 mb level shows the main trough south of 40°S. in the Indian Ocean sector, centred about 100°-110°E. at most seasons of the year, and the main ridge in the western Pacific in the neighbourhood of the outer reaches of the Ross Sea. The mean troughs and ridges have notably smaller amplitude than in the northern hemisphere. The control of trough and ridge positions appears to be thermal rather than orographic, associated with the position of the broadest part of the Antarctic cooling surface, and, at certain seasons, perhaps, with the Eurasian monsoon. Little seasonal movement of the troughs and ridges in longitude is discerned and no very great change of circulation intensity, but there is an intensification of flow and increase of amplitude in the Indian Ocean trough from summer to late winter.

The pattern of glaciation, as well as available data on depression tracks and anticyclone distribution over the Southern Ocean, support the pattern of ridges and troughs at 500 mb here described and throw light upon the occurrence of blocking in various sectors of the southern hemisphere.

An important proposition suggests itself from this study, namely that it may be the momentum and energy of the southern westerlies which are ultimately responsible for maintaining the meteorological equator on average north of the true (geographical) equator, at least over the oceans. The marked deficit of pressure south of 50-60°S. by comparison with the rest of the world may be attributable to ageostrophic effects at the level of the most intense upper westerlies. In any climatic epoch when the southern westerlies were

(i) farther south than now,
and/
or (ii) weaker than now,

the meteorological equator should under this proposition be nearer the true equator than is now the case. (The work of other investigators has suggested that the equatorial low pressure belt should also be wider at times when the circumpolar westerlies weaken in either hemisphere.) These postulated changes appear to fit in with what is known of conditions around the culminating phase of the "Little Ice Age" in the northern hemisphere about a century and a half ago.

1. Introduction

Monthly mean maps of the 500 mb surface over the southern hemisphere for each month from December, 1951 to November, 1954 have been published in NOTOS (1). The network of upper air stations used has been given by Schmitt (2), and is repeated here for ease of reference. On fig. 1 have been added indications of the few points on and near the Antarctic continent for which upper wind and temperature soundings have been available at some time since 1945. In the same article Schmitt has described the methods used in the daily hemispheric surface and upper air analysis at Pretoria from which grid point values are derived to give the monthly mean 500 mb pattern. The method included derivation of a basic 1,000 mb topography and a map of 1,000-500 mb thickness, each chart once a day with all data for that day plotted which became available within the first six months after the event. The 500 mb topography was obtained by graphical addition, having regard also to the data plotted for that level and to the principle of continuity. The patterns of 1,000-500 mb thickness were completed with the aid of extrapolation of the movement of identified features eastwards, subject to the control imposed by passing over test stations such as the islands of Marion, Heard and Macquarie with their regular radio-sonde ascents. Also use was made of the discovery that at thoroughly oceanic stations the surface dew point in °F is nearly equal to the 1,000-500 mb thickness in dekametres with the 500 omitted. Corrections of 2 to 4 dekametres required in certain areas are systematic and the method appears sufficiently verified by internal controls, at least between South Africa and Australasia. For the eastern South Pacific, the broadest part of South America and the South Atlantic except between 40° and 60°S., the working hypotheses used in constructing the daily charts had to be carried on without available checks within the region.

Whatever doubts might be entertained about the adequacy of the observation network for the individual daily or monthly maps, confidence has been increased by subsequent verifications available in the case of the daily surface maps (3, 4); this must be attributed to some extent to the evident possibility of positioning correctly the large scale features of the main steering currents in the upper atmosphere over the great Southern Ocean. This appears to be also the view of the South African Weather Bureau which has published the monthly mean charts in the belief, expressed by Schmitt, that they "hold possibilities for the study of at least the broad scale features of the upper air flow patterns" (loc. cit.), which should be exploited for research.

The three-year mean pattern yielded by the 36 monthly NOTOS values of 500 mb height and presented here in fig. 2 can safely be used as a good approximation to the true picture. It has not been possible to complete the Pacific Ocean sector north of about 60°S: in this part of the southern hemisphere upper air data must unfortunately be considered quite inadequate. In fig. 2 random errors have certainly been reduced to a small order, and the network hardly allows systematic errors in the large scale features at least between 70°W. and 170-180°E. In any case we shall find it possible to confirm the main features from geographical evidence sufficient to eliminate any suspicion that they result from possible bias of the analyst.

Fig. 3a-d are approximate cross-sections from 90°N. to 90°S. of mean westerly velocity component in the four seasons. Fig. 3a, northern winter-southern summer, is for the sector 30-130°E, which contains nearly the strongest upper westerlies in both hemispheres and at roughly constant latitude throughout the sector. In the other seasons these considerations either do not apply or are less obvious, and therefore the cross-sections have been made to relate to the whole northern hemisphere and the widest sector of the southern hemisphere for which enough data are available. The sections have been constructed from published maps of upper winds over the world (5, 6, 7), amplified by the southern hemisphere maps here given at fig. 2, 6 and 7 as well as those for spring and autumn which are not shown. The mean cross-sections for the northern hemisphere given by Moore (8) have been extensively used.

It is immediately apparent that the southern circumpolar whirl must be considered as the biggest and most powerful limb of the atmospheric circulation over the year as a whole.

A tentative crude integration of the westerly angular momentum in either hemisphere between latitudes 0° and 70° and from the 1,000 mb up to the 100 mb level has been obtained by summing m V cos ϕ , where m stands for mass, V for the westerly component of velocity and ϕ for latitude, in 100 mb layers over each 5° zone of latitude. The sum for each zone was multiplied again by cos ϕ to give appropriate weighting for the differing extent of the various latitude zones. The totals for each hemisphere suggest the following ratios (southern hemisphere ÷ northern hemisphere):-

	Angular momentum of the westerlies	Net westerly angular momentum
	Ratio	Ratio
S. summer - N. winter	0.7	0.6
S. autumn - N. spring	1.3	1.3
S. winter - N. summer	4.4	10.2
S. spring - N. autumn	1.6	1.9
Year (over-all average)	1.4	1.6

The figures for net westerly angular momentum in either hemisphere result from subtraction of the momentum of the easterlies. Experiments with extending the estimates to latitude 80° made no difference to the ratios, and because of the small extent of the high latitude zones it is likely that no significant difference to the ratios could result from incorporating them. Rather greater uncertainty is involved in the estimates of easterly and westerly momentum over the tropical oceans, and the entire Pacific sector of the southern hemisphere has had to be omitted; but these uncertainties are not likely to affect the ratios greatly. Indeed, different forms of computation, summing alternatively angular and linear momentum and estimates of these about a single meridian, were tried and found to have but little effect upon the ratios, since numerator and denominator alike were affected. It seems likely that the ratios are more trustworthy than the necessarily rough totals of momentum derived for either hemisphere: this is borne out by the results of repeated fresh estimates and computations. The most striking point was that some ratios hardly fall below unity even during the southern summer.

The figures point to overwhelming magnitude of the southern westerlies during a considerable part of the year, particularly during the northern summer-southern winter, and on balance over the year as a whole. The very high ratios for June-July-August result from a number of factors: (i) the seasonal weakening of the northern westerlies is particularly great, (ii) the northern westerlies move into relatively high latitudes, (iii) the momentum of the tropical easterlies becomes quite large in proportion to the momentum of the northern westerlies - this situation does not arise in the same degree in the southern hemisphere summer, partly because the southern climatic zones are nearer the equator.*

/It

* The following seasonal ratios of gross easterly to gross westerly angular momentum resulted from these calculations:-

Northern hemisphere	Southern hemisphere
Summer 0.58	Summer 0.18
Winter 0.09	Winter 0.02

It has long been appreciated that the southern westerlies were stronger than their northern counterparts, but these are believed to be the first numerical estimates of the ratio. It is to be noted that the overweight of momentum in the southern westerlies is plainly most marked in the lower troposphere, for which most data are available, between the surface and 500 mb; the result does not greatly depend on the (probably cautious) values here selected for 300 mb and higher levels, chiefly taken from Jenkinson (7). Revised values for high levels over the Southern Ocean would probably raise the ratios slightly, so that the best values of the ratio for the southern summer-northern winter are likely to be in the region of 0.8 and for the year as a whole in the range 1.5 to 2.

The seasonal change is greater in the northern than in the southern hemisphere, the respective winter/summer ratios of angular momentum in the westerlies being 4.1 and 1.5. Greater seasonal change of latitude as well as of intensity in the northern hemisphere contributes to this result.

Angular momentum in the southern westerlies appears to be greater than in the northern westerlies over the longitude ranges defined in fig. 3a and 3c, summer for summer in the ratio 2.9 and winter for winter in the ratio 1.1.

The over-all average southern hemisphere/northern hemisphere ratio of westerly linear momentum is two to two and a half.

Schell (9) has noted that G.T. Walker found more significant lag correlations between centres of action in the southern hemisphere and later conditions in the northern hemisphere than were found within the northern hemisphere itself. Lag correlations within the southern hemisphere were over three times more numerous. These discoveries may perhaps be regarded as expressions of the dominance of the momentum in the southern westerlies.

There is clearly a pressing need to survey the broad characteristics, probable associations and range of influence of the system.

2. Characteristics of the southern circumpolar whirl

The prominent characteristics of the southern hemisphere whirl (fig. 2) about which we can be sure may be described as follows:-

2.1. Smaller latitudinal amplitude of waves in the mean circumpolar westerlies than in the northern hemisphere

The mean pattern shows no troughs and ridges of comparable amplitude to those found between 50° and 90°N. (See for comparison the 3-year mean 500 mb contour pattern over the Arctic, fig. 4, given by Flohn (10).)

The apparent circularity of the over-all mean circulation in the southern hemisphere is not produced by any tendency for large amplitude oscillations to occur indifferently scattered over all longitudes in the Southern Ocean. There are preferred longitudes for the troughs and ridges, but these are for the most part of modest amplitude by comparison with those of the northern hemisphere, at least when averages are taken over a period of a month or longer.

To some extent the preferred longitudes for mean troughs or ridges result from successions of mobile features regularly attaining their greatest amplitude about these positions but stationary broad troughs and ridges of modest amplitude by northern standards also enter in.

2.2.1. Trough and ridge positions

Identification of the positions of the mean troughs and ridges is most easily seen from profiles drawn along the latitude parallels (fig. 5a). Similar profiles for the individual seasons (fig. 5b) repeat most features of the overall average.

The most striking points are:-

(i) In latitudes south of 45°S. the trough downstream from the Andes is less pronounced than the broad trough in the Indian Ocean sector with its axis about 100°-110°E.* Between 20° and 45°S. the trough in the western South Atlantic is possibly the biggest feature, in agreement with the deductions of J.A. Boffi from depression tracks and pilot balloon data (13).

(ii) There is a ridge over the Andes to about 50°S., but from 50° to 70°S. (and possibly even north of 50°S.) the ridge in the western Pacific (150°E.-150°W.) is a much more noticeable feature. The northern end of the latter ridge is close to New Zealand, but the situation in the zone of weaker flow over temperate latitudes here is out of phase and New Zealand itself appears rather in a trough.

(iii) There is a secondary ridge, unmistakable in 20°-50°S., between the longitude of South Africa and 40°- 60°E.

(iv) Any seasonal shifts of longitude of the troughs or ridges (fig. 5b) such as might imply lengthening or shortening wavelength appear rather ill marked apart from possible westward displacement of the broad Indian Ocean trough in summer to about 60°E. (Tentative estimates both of the mean and modal wind direction at 3,000 and 6,000 m. at Heard Island (53°S.,74°E.), based on seven months' radio theodolite wind data in 1953 and supported by several years' experience of pilot balloon data, were close to 270° in summer and close to 260° in the other seasons.) Few, if any, other seasonal shifts of trough position seem likely to prove authentic. By and large, there appears to be substantial constancy of the positions of the main troughs and ridges in different seasons. The prevailing direction shown by pilot balloons and cloud observations at medium and high cloud levels appears to be about 290° at all seasons at Macquarie Island (55°S., 159°E.).

The rather surprising weakness of the mean trough in the southern part of the South Atlantic is confirmed by the resultant mean wind for the 36 months from the Stanley, Falkland Islands (51.7°S., 57.9°W.) radiosonde ascents, namely 264°, 33 kt. This figure fits well with fig. 2 both as to direction and strength. The resultant mean winds at Stanley for the three summers, 259°, 38 kt., and for the three winters, 265°, 28 kt., fit equally well with fig. 6 and 7. It is a peculiar feature of this part of the hemisphere that the 500 mb winds as shown by maps and confirmed by the observed values are weaker in winter and spring than in summer and autumn. The summer maximum is believed to affect the winds at Stanley at all heights from the surface up to 200 mb: it is also seen in the surface winds at South Orkney (Signy Island). In some individual months at Stanley the mean 500 mb wind is reported to be from a point somewhat north of west, implying a ridge downstream from the longitude of the Andes.

/The

* That the main trough is a broad feature occupying the Indian Ocean sector agrees with the preliminary results reached by Schmitt (11). According to Schmitt, and also to Heastie (12) working independently, the axis of the trough in summer is rather in the western part of the Indian Ocean sector in longitudes 50°-70°E. The summer profiles at 40° and 60°S. here shown in fig. 5b tend to support this position. There are hints that in latitudes 30°-40°S. the trough may split in summer into two troughs near 50° and 100°E. The all-year profiles (fig. 5a) for the lower latitudes 20° and 30°S. also suggest a trough in the western part of the Indian Ocean sector (60°-90°E.).

The Andes, with peaks reaching 22,000 ft. (6,500 to 7,000 m.) at various latitudes between 9° and 33°S., are higher than the Rockies, but there are no peaks reaching 10,000 ft. (3,000 m.) south of 50°S. The New Zealand Alps exceed 12,000 ft. (3,700 m.) near 40°S., but their latitudinal extent is only about 5°. The main flow of the upper westerlies at 500 mb appears to pass south of both the Andes and the Southern Alps, though it is reported that the peaks of the Bolivian Andes near 23°S. are at times swept by violent westerly storms associated with the high-level subtropical jet stream (14).

The trough in the 500 mb flow in the Indian Ocean sector cannot be attributed to any orographic barrier in the mainstream of the upper westerlies between 40° and 60°S. This trough is not only the biggest on the 3-year mean map: it was also judged to be the biggest on about 70 per cent of the individual monthly maps. It may be plausibly associated with the eccentric position of the broadest part of the Antarctic continent, the effective centre of whose cold radiating surface is displaced from the pole towards this sector. The mean position of the centre of the whole region of Antarctic ice has been calculated as 86°S., 50°E.; the centre of the permanent icesheet of East Antarctica may be taken as about 81°S., 70°E.

The shape of Antarctica in eastern longitudes corresponds fairly well with that of the broad trough in the Indian Ocean sector, where the 3-year mean 500 mb isopleths run parallel with the general run of the coast. The ridge in the western Pacific also corresponds well with those longitudes where the coast of Antarctica lies farthest south. The average latitude of the edge of the permanent ice between 180° and 100°W. may be taken as 70°S., that of the coast as 75°S.

It is hard to avoid concluding that south of 45°S. the dominant control in determining the positions of troughs and ridges in the main atmospheric flow aloft is thermal.

2.2.2. Polar outbreaks

The paths of frequent outbreaks of polar air at the surface appear to fit the 3-year mean 500 mb pattern (fig. 2), and inasmuch as they have been known (for instance, to the whalers) for many years they tend to confirm the validity of this pattern over a much longer term of years.

Vowinckel (15) shows the maximum frequency of polar outbreaks revealed by analysis of 160,000 ships' observations near 64°S. (period 1920-1955) as occurring over a broad sector centred about 110°E. Frequencies were only slightly lower in all longitudes between 60° and 150°E. Apart from any possible loci of outbreaks in the Pacific sector (not investigated), only a much narrower region between 60° and 35°W. comprising the western and central parts of the Weddell Sea can compare with the Indian Ocean - Australian sector.[*]

Another preferred region for polar outbreaks just east of the northern tip of Enderby Land (66°S., 52°E.) has also been suspected, though this may be little more than a local effect superimposed on the general high frequency in the Indian Ocean sector.

The Weddell Sea outbreaks sweep north and northeast to affect all parts of the South Atlantic (16, 17) and sometimes turn east into the Indian Ocean.

/Cold

[*] The most northerly positions reached by occasional icebergs, under the combined influence of surface winds and water currents, are in the western South Atlantic and central Indian Ocean, in both cases about 35°-40°S.

Cold air from the South Polar Plateau and the vast interior of East Antarctica appears to flow out almost continuously over the Adélie Land coast and in a broad, generally ESE'ly, airstream over the fringe of Antarctica in the Indian Ocean sector between 150° and probably 50°E. This constancy is linked with the very great frequency of anticyclones centred near 80°S., 60°E. (cf. fig. 10-12). The common southerly blizzards near McMurdo Sound and in the western Ross Sea near 70°-75°S., 160°-170°E. may be seen as a branch of the same major outflow of cold air. Results from a few sample observational records from diverse periods, which bear witness to this quasi-permanent air current, are given in Table 1. Snow Hill (east side of Grahamland), Maudheim and Bay of Whales are included for comparison, to show the changes of dominant direction and rather greater scatter in other sectors.

Table 1. Frequencies per cent of various surface wind directions at open sites in East Antarctica and at certain other points for comparison

Position and period	N	NE	E	SE	S	SW	W	NW	Calms
Mawson (18) 67°S., 62°E. June-Oct. 1956	1	2	11	59	9	3	2	0.5	13
Gauss (19) 66°S., 90°E. 1902-3 (12 months)	0	2	57	11	5	3	9	2	11
(The Grottoes, 66°S., 95°E. (1912-13 (Shackleton Ice Shelf (20) ((10 months)	0	0	35	48	3	2	4	1	4
Pionerskaya (18) 70°S., 95°E. June-Oct. 1956 2,700 m. a.s.l.	0.4	0.6	11	76	10	1	1	0.2	0
(Port Martin, (Adélie Land (21) 67°S., 141°E. (1950-51	1	2	4	58	23	2	1	1	8
Snow Hill (19) 64°S., 57°W. 1902-3 (1½ years)	3	13	5	1	15	38	7	1	17
Maudheim (22)* 71°S., 11°W. 1950-52 (22 months)	0	14	52	4	18	9	2	0	-
(Bay of Whales, (Ross Ice Shelf (19, 23) 78°S., 166°W. 1911-12, 1929-30, 1934-35, 1940-41. (4 years)	4	5	32	10	19	16	4	1	8

The outflow of cold air from East Antarctica is only partly katabatic in origin, and differs from the Greenland katabatic wind in giving rise to cold airmasses of great depth over the ocean.

/2.2.3.

* The data for Maudheim are provisional, being based upon occasions when the wind was $\geq$ 5 metres per second.

2.2.3. Intensity and breadth of the main belt of southern upper westerlies

The over-all range of yearly mean 500 mb height between the tropical and polar zones in the southern hemisphere, shown on fig. 2, materially exceeds the range in the northern hemisphere: this implies a greater total zonal circulation of the atmosphere over the southern hemisphere, as confirmed by fig. 4.

The greatest yearly mean 500 mb heights are believed to be about 5,900 m. (cf. (14)), over the high-level stations of the Bolivian Altiplano (la Paz 17°S., 68°W.) and 5,870 to 5,880 m. over the central African highlands. The nearest approach to these figures in the northern hemisphere, according to information supplied by the Upper Air Climatology Branch, appears to be in Mexico and the south-western United States - Mirida 21°N., 89°W., 5,883 m., Tacubaya 19°N., 99°W., 5,866 m., Mazatlan 23°N., 106°W., 5,852 m., Lake Charles 30°N., 93°W., 5,824 m. (It is probable (14) that the existence of the raised heating surface in low latitudes contributes to this result: raised surfaces of comparable extent in the northern hemisphere, e.g. Arizona and the Mexican highlands, Spain, Anatolia, Persia, Afghanistan and Tibet, are mostly well north of 25°N. and get too cold in winter to produce such high annual values of the 500 mb surface.

Heights over Cocos Is. (12°S., 97°E.), 5,870 m., and the equatorial zone of the South Pacific near the Gilbert and Ellice Islands (0-10°S., 170-180°E.) 5,850 m. also appear to exceed northern hemisphere equivalents: these places are remote from cold water currents and in or near the regions of warmest extensive ocean surfaces in the world (see (24), page 37).

The lowest yearly mean 500 mb heights over Antarctica, 4,920 to 4,990 m., indicated by the NOTOS charts with support from radio-sonde observations at Little America (1940-41), Maudheim (1950-52), and Port Martin (1951-52) are some 300 metres below the lowest in the Arctic (cf. fig. 4). Rather more than half of this disparity appears to be attributable to the prevalence of M.S.L. pressures about 15 to 25 mb lower in the Antarctic than in the Arctic: there is no obvious disparity between the prevailing pressures in the northern and southern subtropical high pressure belts, so that the surface circulation, like that aloft, shows a greater total of westerly momentum in the southern temperate zone than in the corresponding zone of the northern hemisphere. The rest of the disparity between the 500 mb heights over the Arctic and Antarctic is directly due to the colder Antarctic troposphere, especially in summer. The summer values of mean 1000-500 mb thickness over the Antarctic are 200 to 250 metres lower than over the Arctic. (South of 60°S. precipitation normally falls as snow at all seasons.) The winter thickness values are however similar in both northern and southern polar regions.

The steepest thermal gradient is in the Indian Ocean sector, between the trough in the higher latitudes and the particularly warm tropical zone of this ocean. That this thermal gradient must exceed any other in the world at the present epoch is confirmed by the fact that the islands in 50° to 80°E. exhibit climates ranging from fully tropical with tropical vegetation at Mauritius (20°S.) to ice age at Kerguelen (49°S.) and Heard (53°S.).

We should expect to find the strongest upper westerlies in this sector. This is instanced by an extreme wind observation of 300 kt. at 229 mb (11 km.) on 27 September, 1956 at Amsterdam Island (38°S., 78°E.) (25), and fits well with the distribution of average geostrophic speeds at 500 mb overprinted on fig. 2, 6 and 7. The strongest 500 mb gradient in the northern hemisphere on fig. 4 corresponds to a yearly resultant

mean wind of about 42 kt. over a restricted region of the Canadian maritime provinces between 45° and 50°N. This figure is exceeded over most of a 1,200 to 1,500 miles - wide zone between 40° and 60°S., 20-150°E. with peak values slightly over 50 kt. in the annual mean and probably 60 to 70 kt. or rather more in the means between June and October.

2.2.4. Polar front and subtropical jet streams

The maximum winds indicated by the mean 500 mb map correspond to the polar front jet streams over the Southern Ocean. As in the northern hemisphere the subtropical jet stream is at higher levels. It is clearly indicated at about 12 km. on the various published vertical cross-sections (26, 27, 28, 29, 30), but these all suffer severely from lack of data south of 40°-45°S. and do not show the maximum over the Southern Ocean associated with the polar front jet streams at all well.

The greatest average westerly component in the subtropical jet stream probably exceeds 100 kt. in winter in all the longitudes investigated. Over Australia and New Zealand its winter position is 25°-28°S.; in summer it moves south, perhaps as far as 40-45°S., and the maximum is thought to decline to 50-60 kt. The average latitude of this system over the eastern South Atlantic and western Indian Ocean is given rather further south than in the other sectors examined, namely at 35°-40°S. in winter and 40°-45°S. in summer, very much closer to the zone of the polar front jet streams than in the Australian sector.

The mean westerly components at 5 to 6 km. indicated by the published cross-sections for the Atlantic and Indian Ocean sectors agree well with fig. 6 and 7, both as to strength and position. Agreement between the 500 mb charts here illustrated and the published cross-sections in 150° and 170°E. is less obvious, but this is probably because the strongest 500 mb winds in these longitudes are further south - at 55° to 65°S., too far south for the observations used on the cross-sections. Nevertheless all the cross-sections indicate a secondary maximum of wind speed somewhere south of 45°S.

These comparisons suggest that, as in the northern hemisphere, the sub-tropical jet stream has a somewhat separate existence from the jet streams of higher latitudes moving about in association with the polar front though at times coalescences may occur, especially in the Indian Ocean (31, 32, 33). The latitudes of the zone (40°-60°S.) over which the mean winds at 500 mb are stronger than their northern hemisphere counterparts suggest that the disparity is principally associated with the polar front jet streams of the Southern Ocean. It remains to be determined how much of the difference is due to less variability of direction over the southern temperate zone. Since the polar front wanders all over the zone 40° to 60°S., the breadth of the belt with mean wind over 50 kt. at 500 mb may be taken to imply great frequency of high wind speeds at this level in the polar front jet streams.

2.2.5. Seasonal variation

The profiles in fig. 5b credibly indicate a shortening of the wave spacing of troughs and ridges at 40°S. from winter to summer in the South Atlantic and perhaps everywhere from the Andes to the Indian Ocean sector. It is also plain that the amplitude of the Indian Ocean trough is greatest in winter and spring: this feature becomes much less pronounced in summer,* though the great sweep of west-north-westerly

/winds

* During the southern summer the Eurasian winter monsoon forces the inter-tropical convergence south to a mean January position along an arc from 15°S. over Madagascar to 7°S. between 80° and 100°E. and 15° to 18°S. over north Australia. In approximately the same months the higher latitudes of the southern Indian Ocean are invaded by tropical storms, which, however, quickly occlude on their recurving tracks to the southeast.

winds between this and the western Pacific warm ridge is prominent at all seasons: the mean direction becomes almost NW. over the Ross Sea, as may be verified from Simpson's analysis of the frequency of different directions shown by the smoke from the Erebus volcano (4,000 m.) and by medium and high cloud at Cape Adare and McMurdo Sound (34). No regular longitudinal shift of this north-westerly steering current with the march of the seasons can be identified from the evidence here used. Depressions are steered east and southeast in the Australian sector and into the Ross Sea at all seasons.

The pronounced pressure minimum in late winter in the Ross Sea, culminating with normal October M.S.L. pressure about 973 mb (standard deviation circa 3 mb at Bay of Whales, based on 9 years' data for areas in the southern Ross Sea about 78°S.) is associated with depressions steered by the upper north-westerly winds in the Australian sector.

At the peak of this development in September and October low values of mean pressure seem regularly to spread across Antarctica (with the depression track) as far as southern Grahamland and the Weddell Sea. This phenomenon seems related to the seasonal maximum intensity of flow around the great Indian Ocean trough rather than to any noteworthy displacement of the latter.

The summer and winter 500 mb maps (see fig. 6 and 7) and those for spring and autumn (not reproduced) indicate some general northward shift of the zone of maximum wind from summer to winter. Speeds increase in the lower latitudes in winter, whereas in latitudes near 60°S. the maximum is in summer as appears to be the case even at Falkland (52°S.). In the South American sector the thermal gradient over quite a broad range of latitudes is actually stronger in summer than in winter. Meinardus (35) has considered this latter phenomenon, chiefly in terms of surface pressure and temperature gradients, but found supporting evidence in the prevailing speeds of depressions: apparently the combined effect of seasonal shift of latitude of the strongest westerlies and rather small overall seasonal change of strength in the southern hemisphere results in a fairly general summer maximum of the surface winds in 50°-60°S., especially in the South American, Australasian and Pacific sectors. There is however a general intensification of the flow around the broad Indian Ocean trough from summer through autumn to late winter and spring, followed by a rather rapid jump south and weakening of the maximum in early summer. The progression is clearly seen near 70°E., where the maxima in the mean 500 mb flow appear to be:-

Summer (Dec.-Feb.)	60 kt. near 58°S.
Autumn (Mar.-May)	55 kt. near 55°S.
Winter (June-Aug.)	60 kt. near 50°S.
Spring (Sept.-Nov.)	65 kt. near 50°S.

Although the overall seasonal change of maximum speed is not great, there is a noteworthy broadening of the belt of strong flow over the whole Indian Ocean sector from summer to late winter.

The seasonal movement appears to follow that of the ice limit, the maximum 500 mb wind lying some 8° north of the ice limit in this sector at each season.

3. Accompanying phenomena and independent verifications of the dominant upper air pattern

3.1. Incidence of blocking anticyclones

In the northern hemisphere investigators have found that, when the upper westerlies attain great strength over a considerable sector, large amplitude waves usually develop and lead to quasi-stationary blocking

patterns two to three days later with a great and rather persistent reduction of the zonal flow. Paradoxically, the mean speed of the 500 mb westerlies in 40°-60°S. for several months over a very wide sector reaches values that would be high for the northern hemisphere, yet stationary blocking situations are rare.

Fig. 10-12 show the distribution of once-daily positions of all surface anticyclones defined by at least one closed isobar (5 mb spacing) in the summer of 1946-7 (individual positions, half hemisphere) and (by frequency isopleths) in the three summers 1951-4 and three winters 1952-4* Similar maps have been plotted for all seasons of the year and for other years, but are not reproduced. Numbers printed on fig. 13a and 13b show all cases south of 40°S. in the summer and winter of 1952-3 where a stationary anticyclone remained for four days or more centred within 600 nautical miles of the same position and record the number of days. It is found that quasi-stationary anticyclones south of 40°S. are limited to positions over Antarctica and to just three sectors of the surrounding ocean, namely:-

(i) From close to the south coast of Australia to a wider range of latitudes in the western Pacific probably as far as the region near 60°S., 120°-140°W.

(ii) Near the tip of South America and southeast thereof over the region of the Scotia Sea in 60°-65°S.; they are known to occur on rare occasions in longitudes farther east in the South Atlantic sector 50°-60°S.

(iii) The region southeast of South Africa about the Marion and Crozet Islands in 40°-50°S. in the west of the Indian Ocean sector.

Even in these regions the frequencies of stationary anticyclones do not appear to compare with the corresponding zone of the northern hemisphere, and the vast regions where virtually no anticyclones occur (fig.11 and 12), whether stationary or mobile, are unmatched in the north. An identical conclusion seems to have been reached in Pretoria by van Loon (36).

The daily positions of anticyclones over the Southern Ocean south of 40°S. show a preference for the same three sectors of the ocean. They almost entirely avoid the region of the great upper trough in the eastern part of the Indian Ocean sector, and are only really common in the western-central Pacific sector.

van Loon has remarked that, as in the northern hemisphere, blocking shows a pronounced maximum in late winter - early spring, but over the Southern Ocean the preferred positions are east, not west, of the major continents. He believes this means that the explanations favoured in the northern hemisphere in terms of an orographically produced pattern of ridges and troughs do not apply in the south. He prefers to associate the southern distribution with "easy access to warm air".

The present investigation strongly suggests that the three regions of principal occurrence of anticyclones over the ocean south of 40°S. are determined by

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* The consistency observed between the distribution indicated in the summers of 1946-7 (fig. 10) and 1951-4 (fig. 11) lends support to the belief that the observation network, which was much sparser south of 40°S. in the earlier year, has for some time been adequate for the purpose of this type of investigation. (The Pacific sector was not covered by the daily analyses from which fig. 10 was compiled.)

(i) anticyclogenesis occurring to the warm side of the strong west-north-westerly upper windstream in the Australasian sector well downstream from the great Indian Ocean trough. The latitude tends to increase eastwards and in the individual cases the surface anticyclone is presumably east of an upper ridge developing and travelling east into the Pacific.

(ii) and (iii) anticyclogenetic patterns just west of the South Atlantic and Indian Ocean troughs.

These preferred longitudes for anticyclones suggest a confirmation of the dominant upper air pattern.

The preference for the winter season is presumably linked with maximum amplitude of the troughs.

The Pacific sector, especially between 90° and 130°W., appears to be by far the most frequent location of occasional great quasi-meridional (usually NW.-SE.) ridges of high M.S.L. pressure linking the subtropical belt with the Antarctic. The writer has suggested elsewhere (3) that this is the normal mechanism and location both of renewal of anticyclones over Antarctica after relatively cyclonic periods and of the pressure surges which Simpson noted in the Ross Sea, apparently always coming from near 80°S., 120°W.

Blocking patterns do occur fairly frequently over certain parts of the Southern Ocean, and there is no reason to exclude the possibility that they follow periods of excessive zonal flow ("hydraulic jump"); but stationary situations seldom result. The anticyclones over the ocean nearly always tend to drift away east, no doubt because of the great over-all thermal gradient in the zone 40°-60°S. Cells do, however, split off over Antarctica, where there is little thermal gradient, and become stationary there.

Apparently, in the northern hemisphere the great continents in the temperate zone play an important part in permitting stationary patterns to develop, thanks to wide areas of slight thermal gradient often associated with the main winter snow-cover and the development of distorted thermal patterns between oceans and continents in the same latitude zone. In the southern hemisphere, geography does not generally permit large depressions or anticyclones to produce a thermal pattern capable of maintaining the system in a stationary position.

3.2. Depression tracks and the pattern of glaciation

Our knowledge of the commonest depression tracks over the Southern Ocean, supported by the observed distribution of glaciation, provides further confirmation of the general upper air pattern south of 40°S. and implies that the Indian Ocean trough has been dominant for a very long time.

Glaciation depends for its occurrence on sufficient precipitation, associated with cyclonic activity, at temperatures remaining near or below 0°C.

A sample map of the distribution of frequencies of depressions south of 30°S., originally published elsewhere (37), is reproduced as fig. 14 for ease of reference. The main frequency maxima are (i) near 65°S., 20°E. southeast of the South Atlantic trough; (ii) at 62°-65°S. in the Indian Ocean sector between 80° and 120°E.; (iii) along a broad depression path from near 50°S. in the Australian sector into the southeastern part of the Ross Sea; and (iv) in the Bellingshausen Sea near 65°S., 70°W. These positions show the expected associations with the troughs in the 500 mb flow (fig. 2, 6, 7). Depression frequencies all around the zone 60°-70°S. are kept high by the general, though often rather slow, eastward drift of occluded and decaying centres. Occasionally, in many longitudes, these

centres are swung south and west on looped tracks over the fringe of Antarctica under the influence of the circulations of more vigorous, younger depressions over the ocean to the north. The map also indicates several favoured paths and origins for frontal wave disturbances. Data available consistently indicate the lowest mean annual pressure at M.S.L. near 60° to 65°S. in the eastern part of the Indian Ocean sector in 90° to 110°E. where the value is possibly as low as 980 mb.

The long surface pressure trough with its characteristic SE.-NW. axis between the southern anticyclones in 40°-60°S. in the sector New Zealand to 140°W. and and quasi-permanent Easter Island anticyclones near 30°S. in the eastern Pacific is frequently prominent from latitude 70° to 20°S. The southerly winds in this system are the likely explanation of the northward bulge in the frequency of icebergs (fairly commonly reaching 50°S., occasional instances to 45°S.) in the central Pacific between 105° and 135°W. (38). There are some suggestions of a trough in the main flow at 500 mb in the central Pacific near 90°W. corresponding to this feature of the surface pressure patterns.

The most northerly island with many great glaciers - some of which reach the sea - is Kerguelen, an island 70 miles long near 49°S., 70°E., whose summit reaches over 6,000 ft. (1,865 m.). Heard Island, 25 miles long near 53°S., 74°E. with its summit a dormant volcano reaching 9,000 ft. (2,750 m.), is completely glaciated but for a few small ice-free areas on the lower slopes. Bouvet Island (54°S., 3°E.) is a volcanic cone, five miles across at sea level and reaching over 3,000 ft. (935 m.): the summit and the steep northern and western sides are free from ice but often snowcovered; the whole eastern side is under an ice-sheet. South Georgia is a much bigger and very mountainous island in about the same latitude, 100 miles long and 20 miles broad near 54°S., 38°W.: its highest summit reaches about 9,300 ft. (2,840 m.). There is much ice amongst the mountains of South Georgia and some glaciers reach sea level, but the permanent snow line is generally about 2,000 ft. falling to 1,000 ft. (300 m.) above sea level at the northwestern end where glaciation is relatively heaviest. In far eastern longitudes Macquarie Island, which is 18 miles long near 55°S., 159°E. and rises to a summit about 1,400 ft. (430 m.) above sea level, loses all its snow cover in summer. These islands, all in or near the zone 50°-55°S., support the diagnosis that a great, broad, quasi-permanent upper cold trough occupies the Indian Ocean sector, whereas South Georgia and Macquarie Island benefit to some extent from warm ridges, respectively some distance west and east of them.

The great ice-sheet of East Antarctica derives nourishment from snowfall in cyclonic situations all along its fringe, and there is evidence to suggest that depressions and frontal troughs pass inland with fair frequency across the sector between 120°-140°E. and the Ross Sea. The latter systems sometimes move in from the north or northwest and sometimes on recurving tracks from the Ross Sea in the east. However there is little doubt, either from the study of depression tracks or from the prevailing northwesterly winds at 500 mb in the Australian-Ross Sea sector, that the most frequent depressions over Antarctica are systems travelling southeast into the Ross Sea and occasionally crossing right over West Antarctica to the Bellingshausen and Weddell Seas. This means that, for the present, it remains a mystery why West Antarctica, which is very mountainous, with a highest reported peak 20,000 ft. (6,000 m.), appears much less heavily glaciated than East Antarctica; the ice summits are believed to be about 5,000-7,000 ft. (2,000 m.) and 14,000 ft. (4,000 m.) respectively near 75°-80°S., 100-120°W. and 80°S., 50°E. (39). The depression tracks observed at the present epoch would suggest increasing glaciation in West Antarctica and possibly insufficient precipitation to maintain full nourishment of the East Antarctic ice dome.

Continental regions exceeding 1,500 nautical miles in longitudinal extent in high latitudes appear to have a critical importance in establishing a fixed cold trough in the upper air flow (40). A cold trough would presumably therefore be more readily established over East Antarctica than over West Antarctica which is scarcely 1,000 miles across.

3.3. World wide relationships; seasonal and secular variations

There is at all seasons an obvious deficit of M.S.L. pressure, and therefore of atmospheric mass, everywhere south of about 40°S. in comparison with the corresponding parts of the northern hemisphere. Over much of the region this disparity is of the order of 20 mb.

In more detail, calculations based on the best available world maps of average pressure at M.S.L. suggest that the deficiency as compared with the northern hemisphere begins about latitude 45° in the southern winter but extends to all latitudes in the southern summer. Over the year there is an apparent excess of mass over the northern hemisphere as a whole of about a half of one per cent, equivalent to about 5 mb of average M.S.L. pressure; the excess appears to range from about 0.9 per cent in the northern winter to 0.1 per cent in the northern summer.

When allowance is made for the intrusion of elevated land in either hemisphere, the apparent difference of one half per cent of atmospheric mass between northern and southern hemisphere is approximately cancelled out. (Much estimation is involved but the correction is clearly of the same order and seems to be close to the same value.) There is no doubt however of a disparity of over one per cent between latitudes south of 35°S. and north of 35°N. Between 5° and 30°S. the annual figures suggest a small excess over northern hemisphere equivalents. This excess must be at least partly associated with the further fact that the zone of subtropical maximum pressure in the southern hemisphere is about 5° nearer the equator than its northern counterpart when either the respective winter or summer positions are compared.

Various estimations of the mean latitude of the meteorological equator (intertropical convergence) based on latitudes of the subtropical anticyclone centres, limits given by various authors for the doldrums belt in different sectors, penetration of the NE. and SE. Trade Winds and even reported crossing of the geographical equator by old cold fronts principally of southern origin give corroborative figures about 3.5°N. for the over-all mean latitude of the intertropical convergence.* Only in the western Pacific sector, west of about 160°W., is the annual mean position south of the geographical equator (about 3°S.): it is perhaps significant that these are about the same longitudes as those of the main warm ridge in the southern upper westerlies.

It is not so easy on geographical grounds to make a direct comparison of the respective positions of the sub-Arctic and sub-Antarctic zones of minimum pressure, although a mean latitude 60°-65°S. is suggested as against rather north of 65°N.

There is an apparent paradox in the average northward displacement of all the climatic zones** in spite of an actual deficit of mass to the south of them. It seems that the likeliest clues to the physical explanation of this paradox are

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* The actual lines given by various authors for the intertropical convergence are also in general agreement with this figure.

** The latitudes of the ice-covered islands in the Southern Ocean mentioned on page 13 should also be compared with northern equivalents. In Chile the northernmost glacier (San Rafael) from the Patagonian ice-cap reaches the sea in 46° 40'S., ten degrees farther from the Pole than any Alaskan glacier.

(i) the latitudinal position of the main thermal gradient around the respective polar caps

(ii) the outstanding momentum and energy of the southern upper westerlies.

The latter appears to be the more fundamental.

Faust (41), Murray and Daniels (42) and others have noticed over Europe a net ageostrophic transport of air towards the warmer side of the jet stream, which is not confined to the jet stream exit but appears even in the middle of the jet stream and is believed to correspond to a net transport in this sense in the upper troposphere about the general level of maximum wind. Moreover, the ageostrophic transport away from the colder towards the warmer side appears to be in some senses proportional to the intensity of the maximum wind. The observed effect is associated with levels near the maximum wind level and winds at 500 mb probably cannot be used to demonstrate it.

Although this effect ("the Nullschicht effect") is not yet satisfactorily explained, it does suggest a northward transport of mass associated with the strength of the southern upper westerlies.

Comparison of the monthly mean pressure over the southern polar cap with the varying latitude and intensity of the upper westerlies suggests certain associations.

Mean M.S.L. pressures over the polar cap (70°-90°S.) and in the subpolar zone 60°-70°S. were compared with M.S.L. pressure, 1000-500 mb thickness and 500 mb heights and gradients in the zone of westerlies over the best covered longitudes 70°W.-170°E. from monthly data published in NOTOS over periods of up to 41 months. Higher than average pressure south of 60°S. was found, as would be expected, highly significantly correlated with weakened surface pressure gradients for westerly winds in all latitudes south of 45°S. ($r = -0.67$ to -0.77 for 29 to 41 months) and with equatorward displacement of the latitude of strongest surface westerlies ($r = -0.73$ for 29 months). Relatively high pressure south of 60°S. was significantly correlated with below-average values of 1000-500 mb thickness at 60°S. ($r = -0.50$ to -0.65 for 27 months) and showed weaker correlations with lowered thickness also at 50° and 40°S.: there was a suggested, though inconclusively demonstrated, association with increased thickness gradient between 40° and 60°S. ($r = +0.14$ to $+0.35$). There was a suggested association of high pressure everywhere south of 60°S. with weakened westerly flow at 500 mb in 50°-60°S. ($r = -0.11$ to -0.24 over 32 months), equatorward shift of the latitude of strongest flow at this level ($r = -0.27$ to -0.33 over 31 months) and strengthened flow in 30°-40°S. ($r = +0.23$ to 0.40 for 32 months), but none of these relationships was conclusively demonstrated. The most definite upper air correlations were with pressures in the subpolar zone rather than south of 70°S., where M.S.L. pressures are moreover largely fictitious and uncertain.

It appears inevitable that both seasonal and secular climatic trends associated with general strengthening or weakening of the zonal circulation and of the meridional temperature gradients affecting the position or intensity of the southern westerlies should have unlike effects south and north of this system and entail appreciable adjustments over the rest of the world.

Many years ago Meinardus (42) noticed that south of about 50°S. the highest M.S.L. pressures appeared to occur in summer (December-January), in spite of the complication of a double wave in the annual pressure curve in 60°-70°S. in the Weddell Sea-Atlantic sector with another maximum in May or June (44). The "anti-monsoonal" trend appears dominant in the highest southern latitudes, and about 78°S. in the Ross Sea the warm season maximum appears

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to be the only significant one; winter there is a season of low pressure, especially late winter. Meinardus made some calculations of the seasonal exchange of atmospheric mass involved. The null point in this exchange appeared to be approximately the latitude in which the strongest upper westerlies associated with the polar front jet streams are now seen to lie.

Willett (45) and others have noticed unlike climatic trends south of about 40°S. and over the rest of the world. During the period of great warming of the Arctic, for instance, culminating between 1900 and about 1938, latitudes south of 40°S. are believed by Willett to have been colder than formerly, and Kraus has suggested (46) that the westerly disturbances of the Southern Ocean were displaced north to affect Australia more in approximately those years than before or since. Since about 1945 there are signs (15) of an upward trend in surface temperatures over the Southern Ocean south of 60°S. and since about the 1920s of depression tracks keeping gradually farther south in the Australasian sector. This latest trend appears to coincide with a levelling-off of the warming trend over Spitsbergen and northern Europe, possibly the substitution of a rather colder regime with depression tracks somewhat farther south.

There are perhaps indications of opposite climatic trend over the southern polar regions from the rest of the world over a rather longer period: the farthest south positions reached by Cook near 40°E. in 1773 and near 110°W. in 1774 as well as by Bellingshausen in 1820 near the Greenwich meridian and Biscoe in 1831 between 0° and 30°E. were all 1° to 2° of latitude south of the normal limit of pack-ice in recent years at the end of the melting season (47), and in 1823 Weddell found the Weddell Sea almost free of ice - an experience never repeated since. When the frailty of the wooden ships of those days is remembered, it seems clear that the ice limit tended to be some degrees south of its supposed present normal position (as appears to be the view of the Scott Polar Research Institute). Dr. Herdman, however, doubts whether the modern normal is sufficiently determinate for this to be settled. There is nothing surprising in this since year to year variations are considerable and are liable to exceed the supposed change of long-period average position since the epoch 1770-1830.

The same over-all trend might be deduced from the present advanced state of the South Georgia glaciers, which are generally in contact with their side moraines down to sea level and are known to have advanced since the 1880s, but show erratic changes in the past 6 to 12 years. There is apparently no bare rock which has not obviously been exposed to the weather for decades or centuries.

Between 1770 and about 1840 the ice limit in the North Atlantic was near Iceland for much of the year, and it was a cold epoch all over northern Europe (48). The westerly winds on the North Atlantic and over western Europe were less strong, or less prevalent, than now and the climatic zones in this sector of the northern hemisphere were certainly displaced some degrees south from present day experience.

Superimposed upon any tendency for sympathetic shifting of all the climatic zones, it may be that there are periods of general weakening or intensification of the circulation, intensification being commonly held to entail a tendency for equatorward displacement of the main upper westerlies in both hemispheres. Kraus (46, 49, 50, 51) has postulated general intensification of the upper westerlies in both hemispheres from about 1895 to the 1920s or later, causing general intensification of the subtropical anticyclones and narrowing of the equatorial rain-belt. From about the mid 1920s to 1940 however the data seem more consistent with a general northward anomaly of the climatic zones in both hemispheres. Following an apparently sudden northward shift of the southern westerlies in 1893-4, by 1930 to 1940 the northward shift is believed to have affected most sectors of the northern hemisphere also said to have been noticeable in all seasons of the year.

It seems that changes in the southern upper westerlies might affect the general atmospheric circulation over the rest of the world in at least three ways:-

(i) changes of over-all intensity of the circumpolar whirl should be directly related to changes in intensity of the subtropical anticyclones in the southern hemisphere and therewith of the SE. Trade Winds. Such changes bring about changes in the supply of warm water to the Gulf Stream and in the value of Walker's "Southern Oscillation", which involves changes of mean pressure over much of the world. (It may be noted that changes of average M.S.L. pressure south of 50°S. would have about ten times the magnitude of any general compensatory changes of pressure level, if spread evenly over the rest of the world.)

(ii) changes in the mean latitude of the circumpolar whirl in the southern hemisphere are likely to be accompanied sooner or later by small, but probably appreciable, sympathetic shifts of other climatic zones.

(iii) changes of eccentricity of the southern whirl occur over short periods but any long-term changes might imply or require changes in the relative states of ice cover over East and West Antarctica. These can probably be ruled out within the period of our meteorological instrumental record, but might be important in considering the ice ages and epochs lasting several millenia.

REFERENCES:

(1) NOTOS — Vols. 2-4, published Weather Bureau, Pretoria, 1953-1955.

(2) SCHMITT, W. — Upper air analysis for the southern hemisphere. NOTOS, 2, pp. 20-27, Pretoria, 1953.

(3) LAMB, H.H. — Meteorological situations over the south polar regions and alimentation of the Antarctic ice-cap. Association d'Hydrologie Scientifique, Tome I, U.G.G.I., Brussels, 1951.

(4) LAMB, H.H. — Meteorological results of the Balaena expedition 1946-47. M.O. Geophysical Memoir No. 94, London, 1956.

(5) BROOKS, C.E.P.; DURST, C.S.; CARRUTHERS, N.; DEWAR, D. and SAWYER, J.S. — Upper winds over the world. M.O. Geophysical Memoir No. 85, London, 1950.

(6) BANNON, J.K. — Some aspects of the mean upper-air flow over the earth. Proceedings of the Toronto Met. Conference, September, 1953, pp. 109-121, published R. Met. Soc., London, 1954.

(7) JENKINSON, A.F. — Meteorological Research Papers, Air Ministry, London, 1954. No. 823.

(8) MOORE, J.G. — Cross-sections of the mean zonal component of geostrophic wind. Met. Mag., 85, pp. 167-171, London, 1956.

(9) SCHELL, I.I. — The interdependence of weather and atmospheric circulations in the northern and southern hemisphere. Bull. Amer. Met. Soc., 20, pp. 332-333, Worcester (Mass.) 1939.

(10) FLOHN, H. — Zur Aerologie der Polargebiete. Met. Rundschau, 5, pp. 81-87, 121-128, Heidelberg, 1952.

(11) SCHMITT, W. — Preliminary mean absolute topography 500 mb southern hemisphere 70°W. to 120°E. Summer 1951-52. NOTOS, 1, pp. 7-17, Pretoria, 1952.

(12) HEASTIE, H. — Average height of the standard isobaric surfaces over the temperate and tropical regions in January. Meteorological Research Papers, Air Ministry, London, 1957. No. 1045.

(13) BOFFI, J.A. — Effect of the Andes mountains on the general circulation over the southern part of South America. Bull. Amer. Met. Soc., 30, pp. 242-247, Lancaster, Pa., 1949.

/(14)

(14) FLOHN, H. — Zur vergleichenden Meteorologie der Hochgebirge. Archiv für Met., Geophys. und Bioklimatologie Serie B, 6, pp. 193-206, Vienna, 1955.

(15) VOWINCKEL, E. — Das Klima des antarktischen Ozeans, Teil II. Archiv für Met., Geophys. und Bioklimatologie Serie B, 7, pp. 342-369, Vienna, 1956.

(16) BRITTON, G.P. — Pressure waves and their application to long range forecasting in the South Atlantic. Naval Weather Service, Circular No. 12/49, London, 1949.

(17) LAMB, H.H. — Some special features of the climate of St. Helena and the Trade Wind Zone in the South Atlantic. Met. Mag., 86, pp. 73-76, London, 1957.

(18) New Zealand Meteorological Service — Daily Weather Bulletins (Antarctic Section). Wellington (from June) 1956.

(19) MEINARDUS, W. — Klimakunde der Antarktis, Köppen and Geiger's Handbuch der Klimatologie, 4 U., Berlin, 1938.

(20) Australian Antarctic Expedition 1911-14. — Records of the Queen Mary Land Station. Scientific Reports, Series B, Vol. V, Part 1. Sydney (government printer) 1940.

(21) BOUJON, H. — Les observations meteorologiques de Port Martin en Terre Adélie, Fascicule I, Paris (Expéditions polaires françaises) 1954.

(22) SWITHINBANK, C. — Ice Shelves. Geogr. J., 121, pp. 64-67, London, 1955.

(23) COURT, A. — Meteorological data for Little America III. U.S. Monthly Weather Review, Suppt. 48, Washington (Weather Bureau) 1949.

(24) RIEHL, H. — Tropical meteorology. New York (McGraw-Hill) 1954.

(25) SCHMITT, W. — Record wind of 300 knots. News Letter No. 91, p. 7, Weather Bureau, Pretoria, 31st October, 1956.

(26) LOEWE, F. and RADOK, U. — A meridional aerological cross-section in the S.W. Pacific. J. Met., 7, pp. 58-65, Lancaster, Pa., 1950.

(27) HUTCHINGS, J.W. — A meridional atmospheric cross-section for an oceanic region. J.Met., 7, pp. 94-100, Lancaster, Pa., 1950.

/(28)

(28) FLOHN, H. Grundzüge der allgemeinen Zirkulation auf der Südhalbkugel. Archiv für Met., Geophys. und Bioklim. Serie A, 2, pp. 17-64, Vienna, 1950.

(29) van Loon, H. A note on meridional atmospheric cross-sections in the southern hemisphere. NOTOS, 4, pp. 127-129, Pretoria, 1955.

(30) GIBBS, W.J. A comparison of hemispheric circulations with particular reference to the western Pacific. Quart. J., R. Met. S., 79, pp. 121-136, London, 1953.

(31) PALMEN, E. Über die atmosphärischen Strahlströme. Met. Abhandlungen der Freien Universität Berlin, Band II, Heft 3, pp. 35-49, Berlin, 1954.

(32) BANNON, J.K. Note on the subtropical jet stream in January and April, 1951. Met. Mag., 83, pp. 257-263, London, 1954.

(33) LAMB, H.H.; FLEMING, J.; HOYLE, H.D. and ROBINSON, J. Jet streams over North Africa and the central Mediterranean: January and February, 1954. Met. Mag., 86, pp. 97-111, London, 1957.

(34) SIMPSON, G.C. British Antarctic Expedition 1910-13; Meteorology, Vol. I. (Discussion) pp. 133-135, Calcutta, 1919.

(35) MEINARDUS, W. Die jährliche Periode der meridionalen Luftdruckgradienten und der Windstärken auf der südlichen Halbkugel. Met. Rundschau, 1, pp. 134-137, Heidelberg, 1947.

(36) van LOON, H. Blocking action in the southern hemisphere. NOTOS, 5, pp. 171-3, Pretoria, 1956.

(37) LAMB, H.H. and BRITTON, G.P. General atmospheric circulation and weather variations in the Antarctic. Geogr. J., 121, pp. 334-349, London, 1955.

(38) SHAW, N. Manual of Meteorology, Vol. II, p. 19, Cambridge, 1936.

(39) SHARP, R.F. Antarctic Glaciological Research. Antarctica in the International Geophysical Year, pp. 27-35. American Geophysical Union, Geophysical Monographs No. 1, Washington, 1956.

(40) LAMB, H.H. Two-way relationship between the snow or ice limit and 1000-500 mb thicknesses in the overlying atmosphere. Quart. J., R. Met. Soc., 81, pp. 172-189, London, 1955.

(41) FAUST, H. Übergradientische Winde in der Nullschicht und das Problem der Strahlströme. Archiv für Met., Geophys. und Bioklim., Serie A, 8, pp. 45-71, Vienna, 1955.

(42) MURRAY, R. and DANIELS, S.M. Transverse flow at entrance and exit to jet streams. Quart. J., R. Met. S., 79, pp. 236-241, London, 1953.

(43) MEINARDUS, W. Die mittlere Höhe und Eisbedeckung der Antarktis. Nachrichten der Gesellschaft der Wissenschaften zu Göttingen, Math. - Phys. Klasse, 1927.

(44) SCHWERDTFEGER, W. and PROHASKA, F. Der Jahresgang des Luftdrucks auf der Erde. Met. Rundschau, 9, pp. 33-43, Heidelberg, 1956.

(45) WILLETT, H.C. Temperature trends of the past century. R.Met.Soc. Centenary Proceedings, pp. 195-206, London, 1950.

(46) KRAUS, E.B. Secular changes in the rainfall regime of S.E. Australia. Quart. J., R. Met. S., 80, pp. 591-601, London, 1954.

(47) MACKINTOSH, N.A. and HERDMAN, H.F.P. Distribution of the pack-ice in the Southern Ocean. Discovery Reports, Vol. XIX, pp. 285-296, Cambridge, 1940.

(48) KOCH, L. The East Greenland Ice. Meddelelser om Grönland, Bd. 130, Nr.3, Copenhagen, 1945.

(49) KRAUS, E.B. Secular changes of east-coast rainfall regimes. Quart. J., R. Met. Soc., 81, pp. 430-439, London, 1955.

(50) KRAUS, E.B. Secular changes of tropical rainfall regimes. Quart. J., R. Met. Soc., 81, pp. 198-210, London, 1955.

(51) KRAUS, E.B. Secular changes of the standing circulation. Quart. J., R. Met. Soc., 82, pp. 289-300, London, 1956.

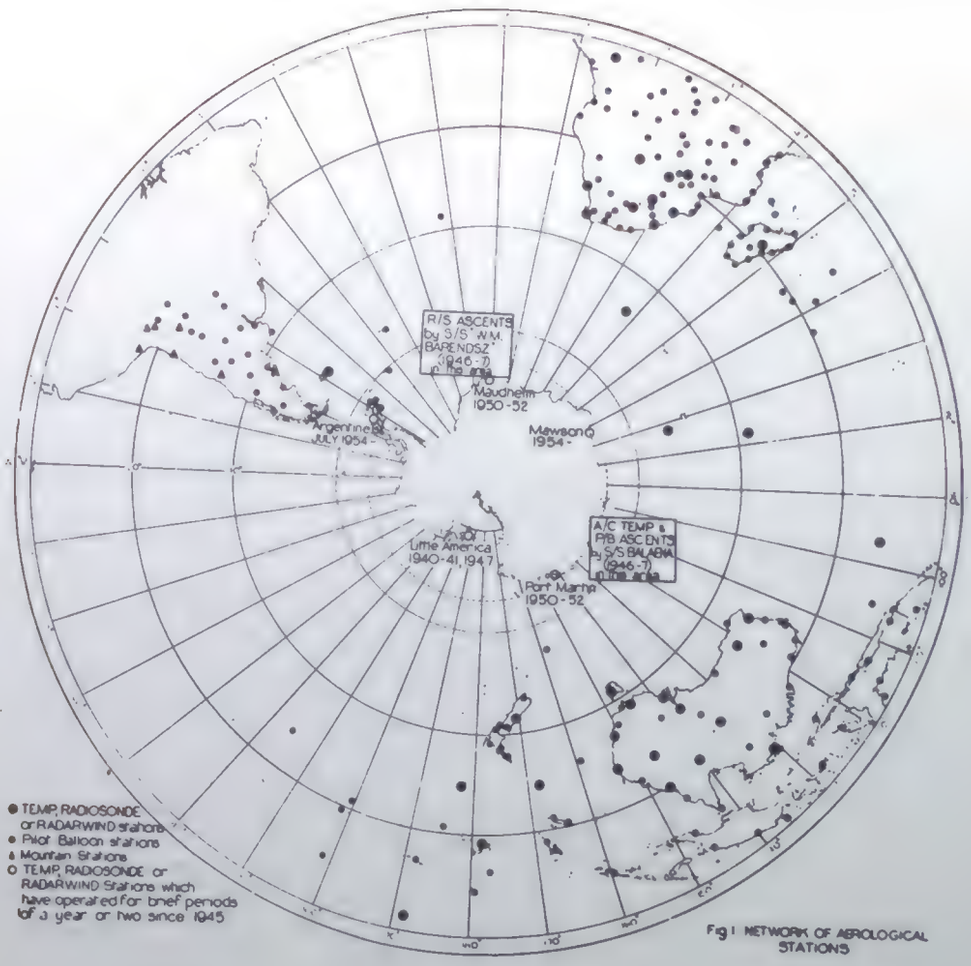


Fig 1 NETWORK OF AEROLOGICAL STATIONS

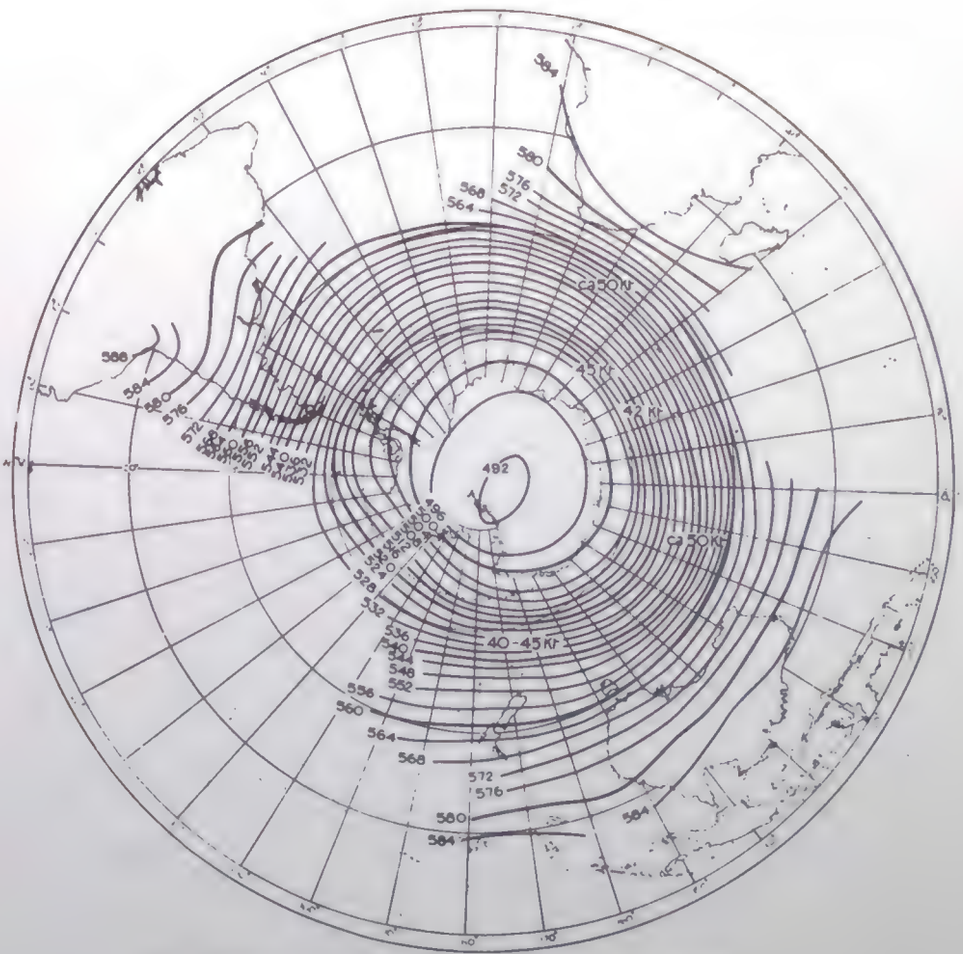


Fig 2. 3-YEAR MEAN HEIGHT OF 500 mb SURFACE IN DEKAMETRES DEC. 1951 - NOV. 1954

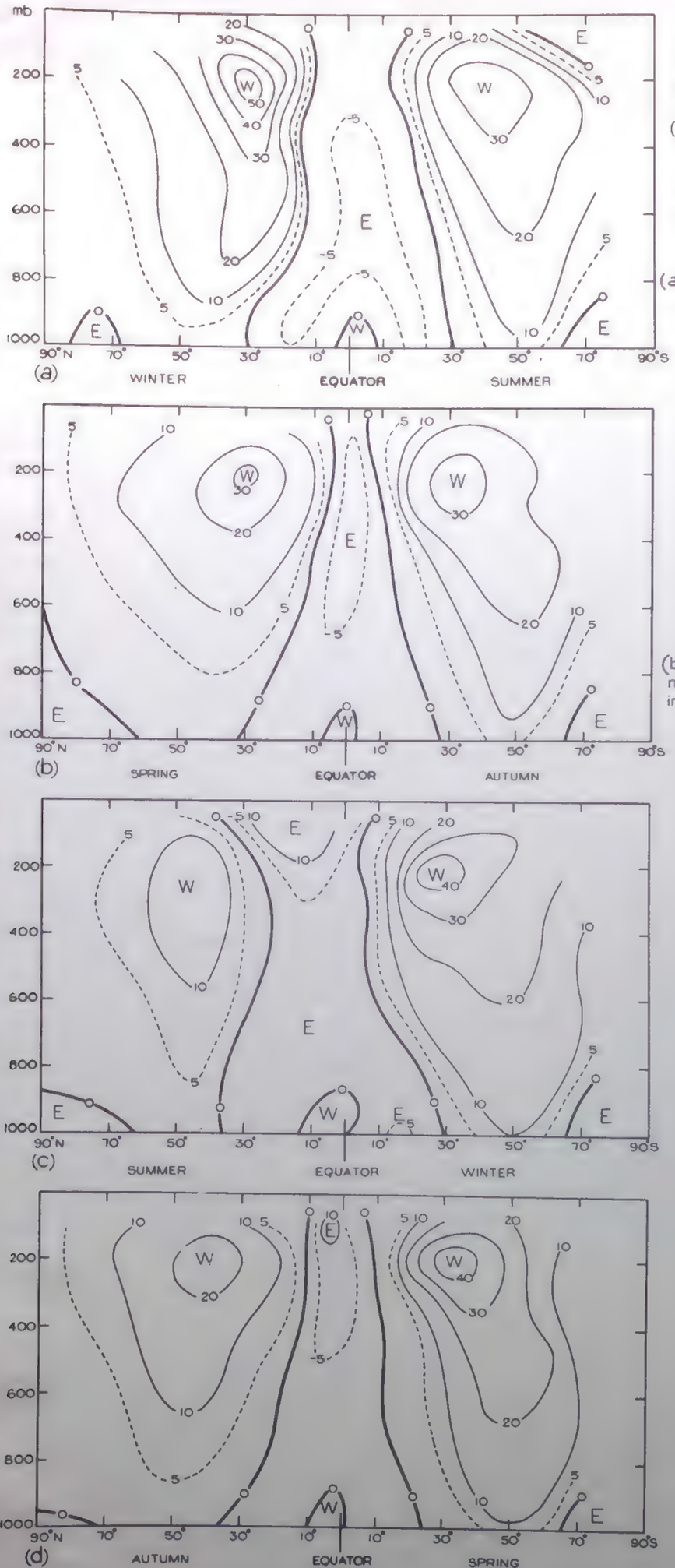


Fig.3
CROSS SECTIONS OF THE MEAN WESTERLY COMPONENT OF VELOCITY
(used in momentum ratio computations)

Velocities in metres per second

(a) 30-130°E. in both hemispheres

(b) (c) and (d) all longitudes in northern hemisphere, 70°W-170°E. in southern hemisphere

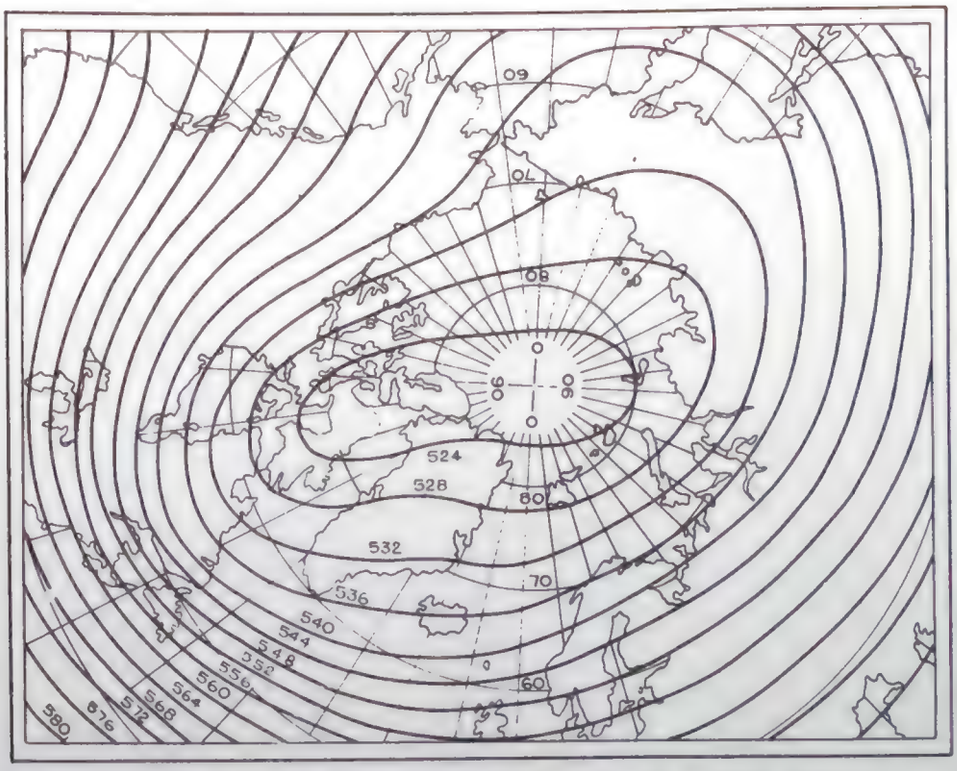
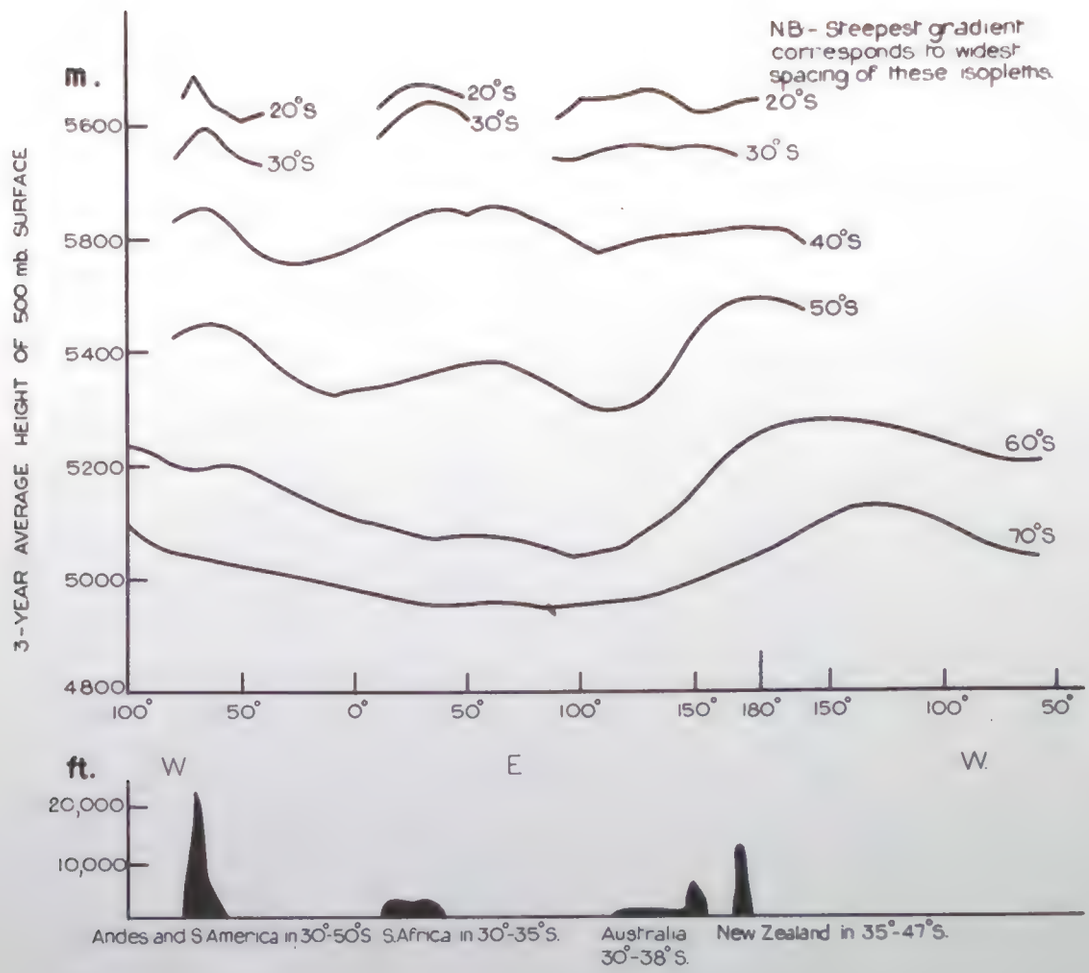


FIG. 4 3-YEAR MEAN 500 mb. HEIGHT, IN DEKAMETRES (1949-51) NORTHERN HEMISPHERE.

(AFTER FLOHN.)



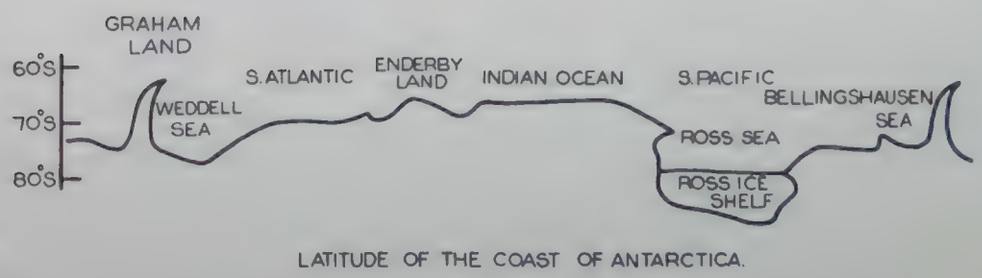


Fig. 5a. 3-YEAR MEAN PROFILES OF THE 500 mb. SURFACE ALONG EACH 10° PARALLEL OF LATITUDE (DEC 1951 - NOV 1954)

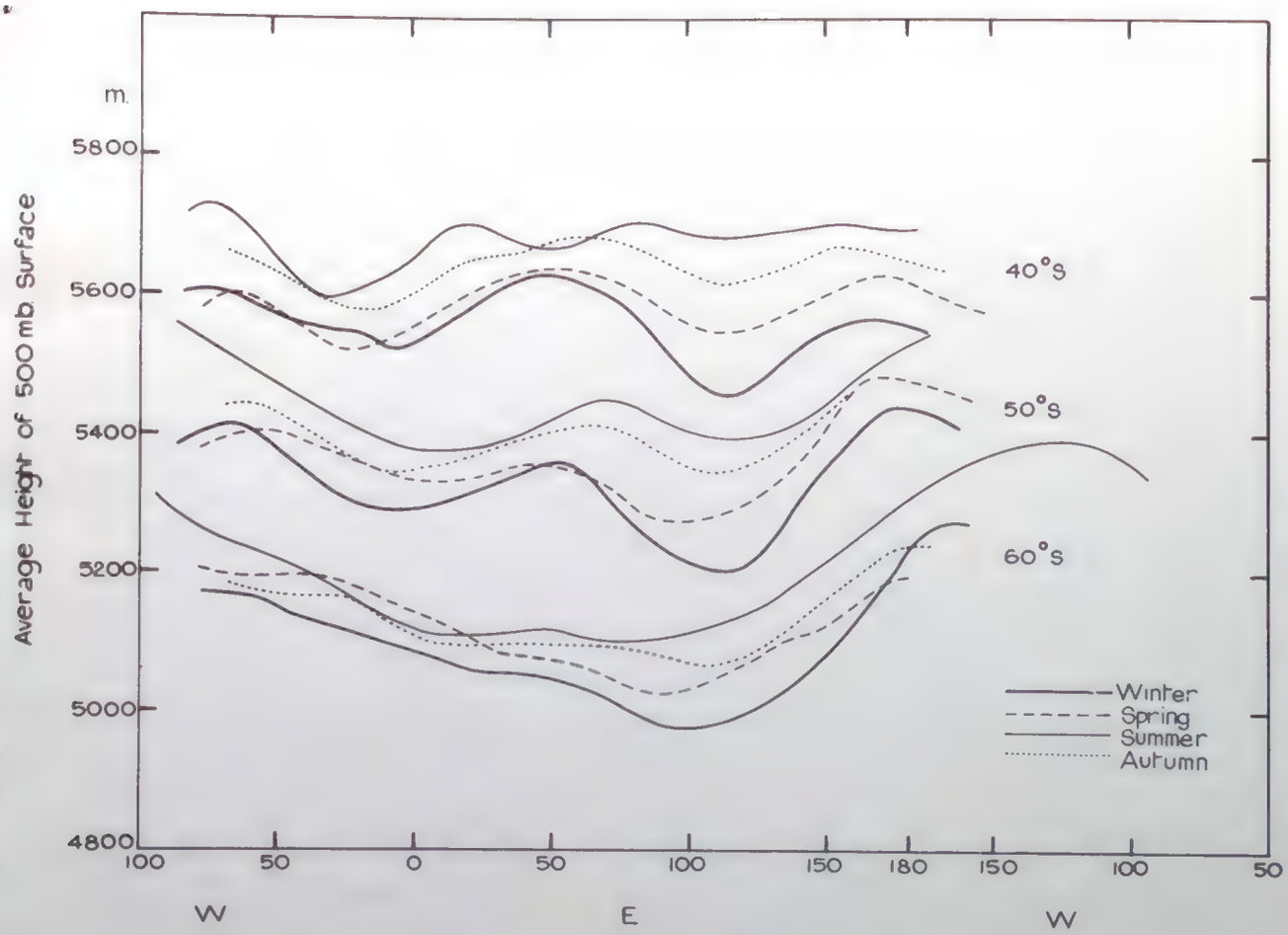


Fig. 5(b) SEASONAL PROFILES of 500 mb. HEIGHT ALONG 40°S, 50°S and 60°S. 1952 - 54.

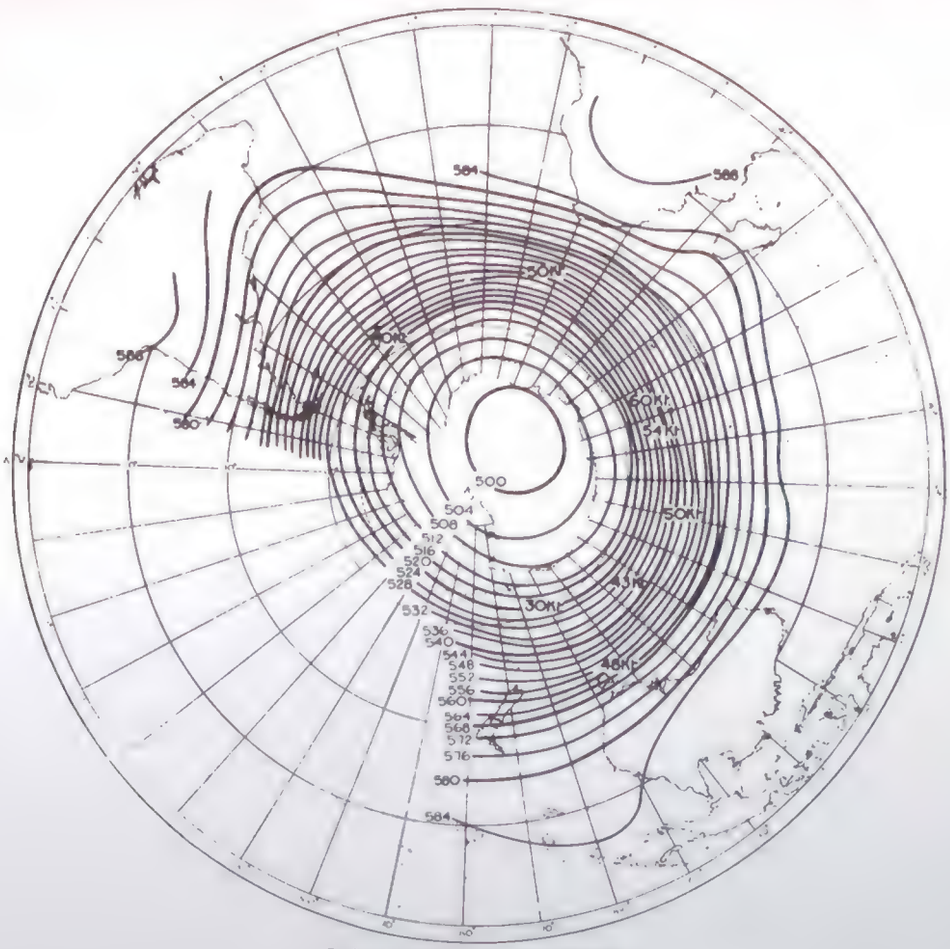


Fig 6. MEAN 500 mb HEIGHTS (SUMMER)
(THREE SUMMERS)
1951-4

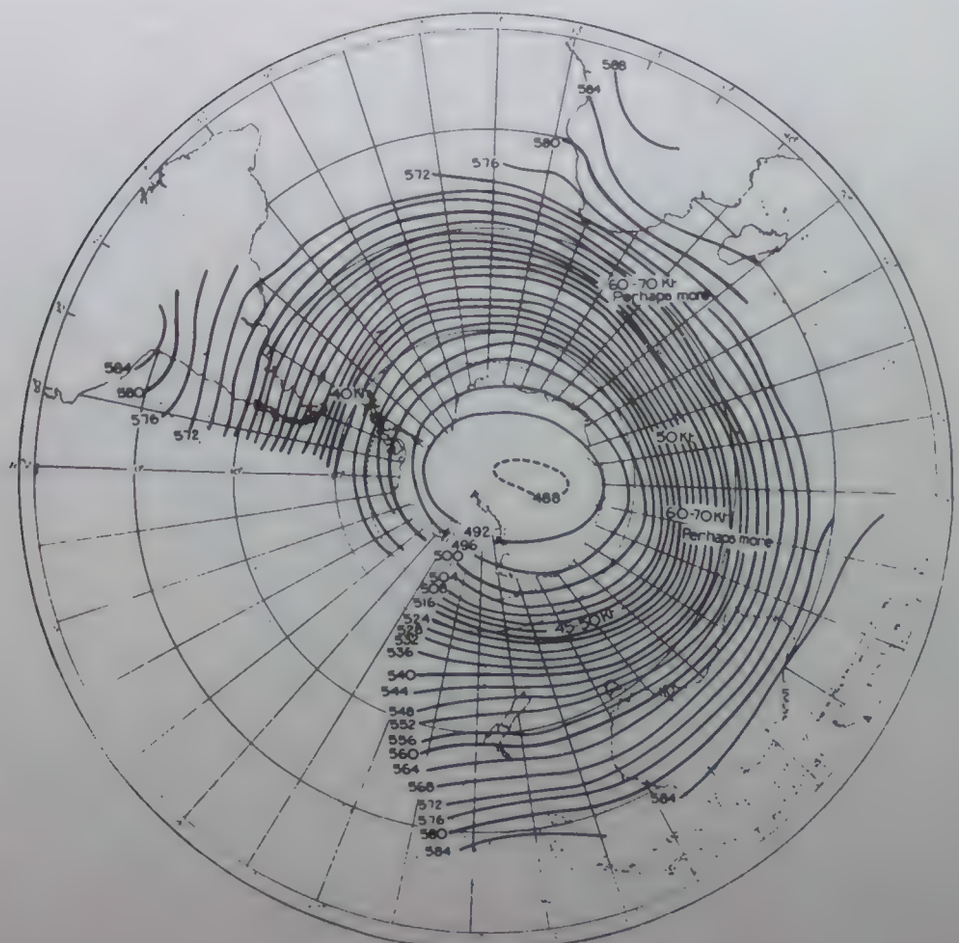


Fig 7. MEAN 500 mb HEIGHTS (WINTER)
(THREE WINTERS)
1952-4

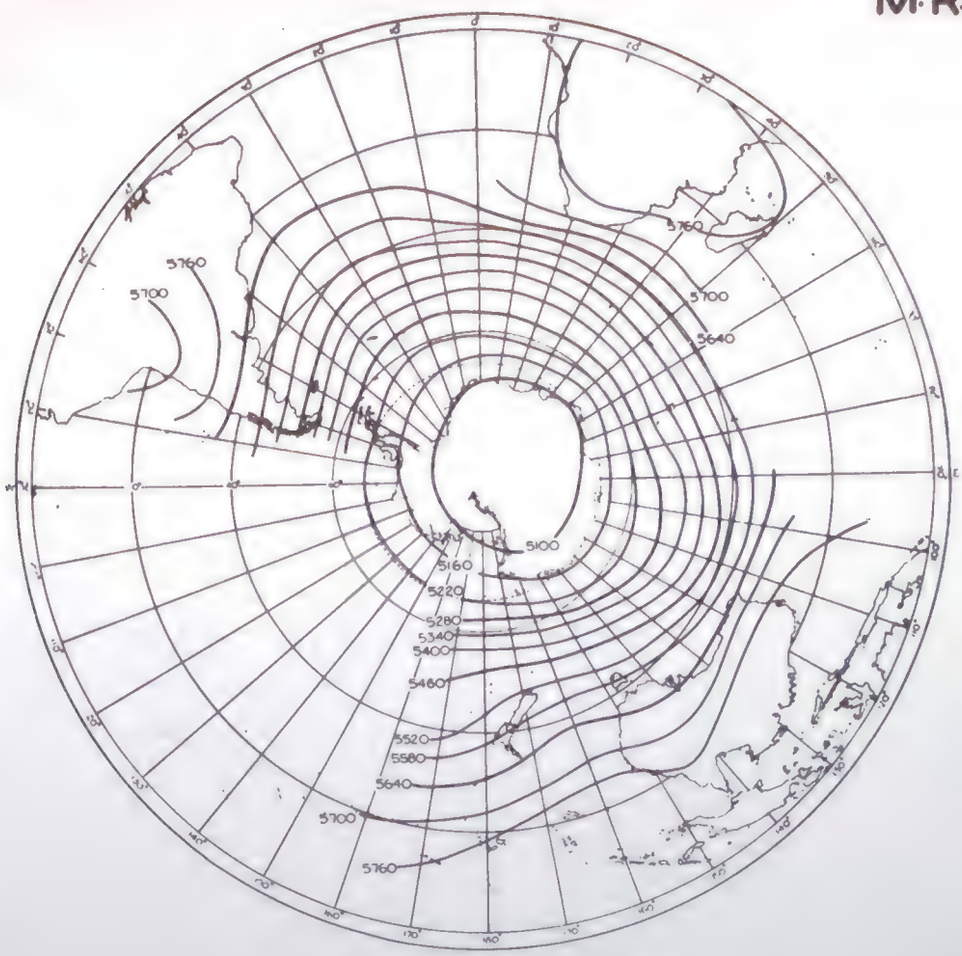


Fig 8 Mean 1000-500 mb Thickness (Summer)
in metres
1951-4

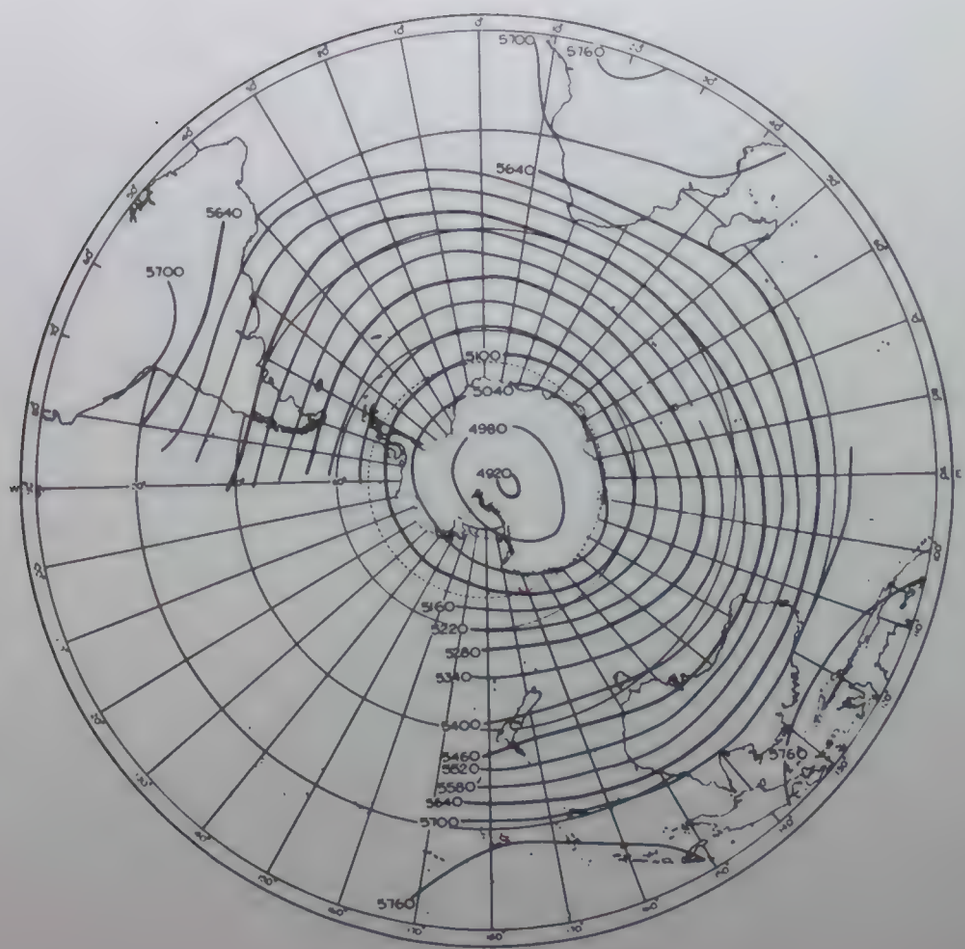


Fig 9 Mean 1000-500 mb Thickness (Winter)
in metres
1952-4

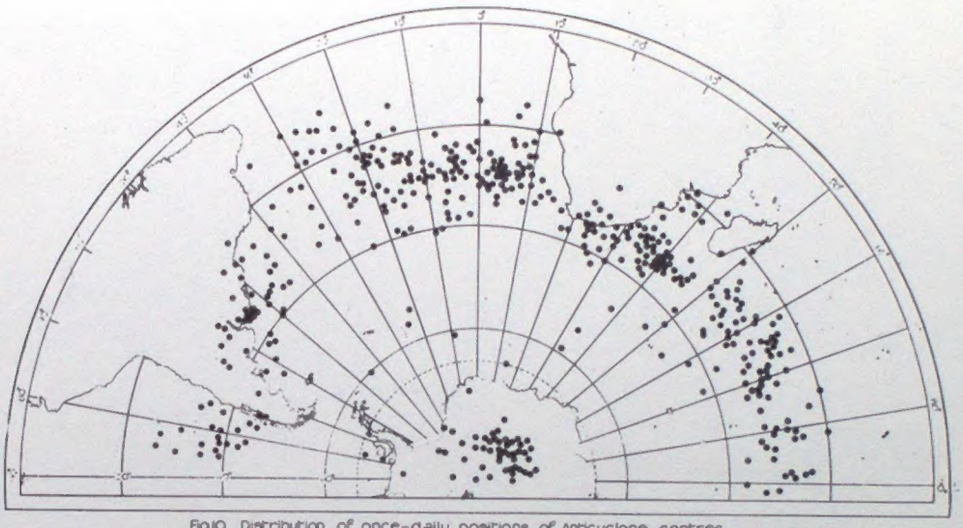
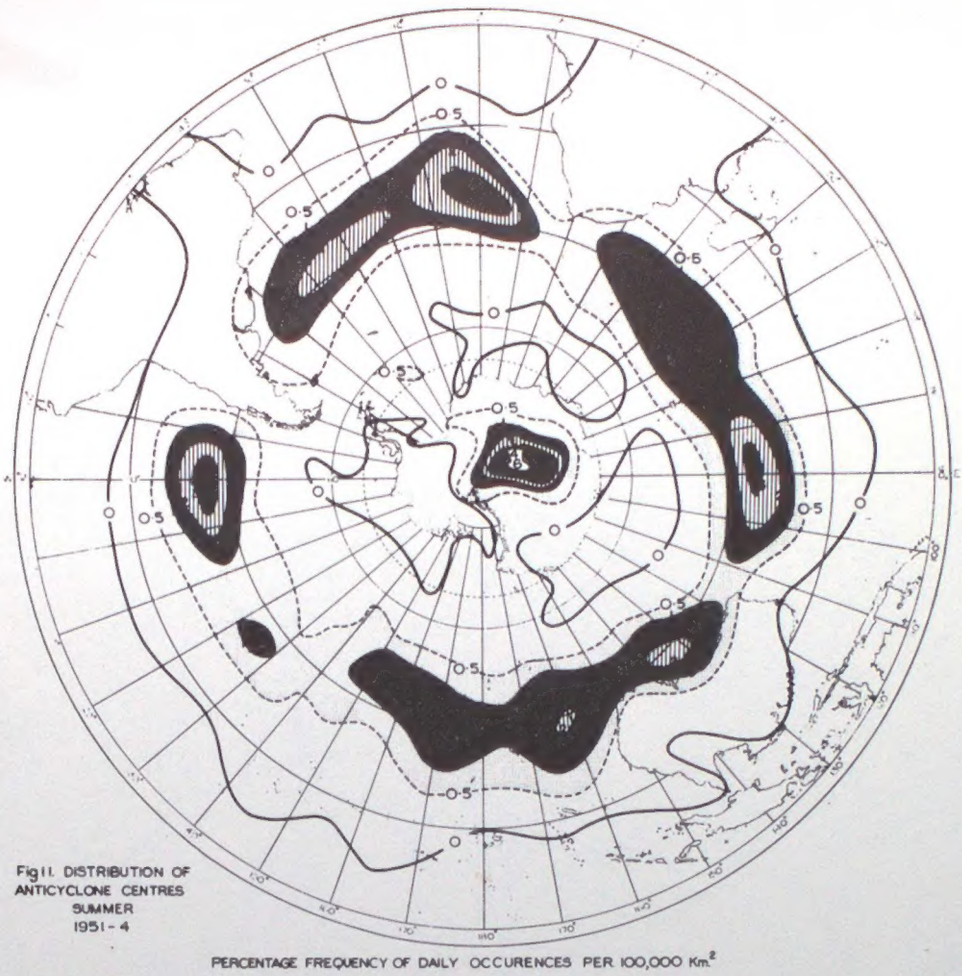


Fig10 Distribution of once-daily positions of Anticyclone centres
SUMMER 1946-7 (Dec-Feb)


0·5
0·5
0·5

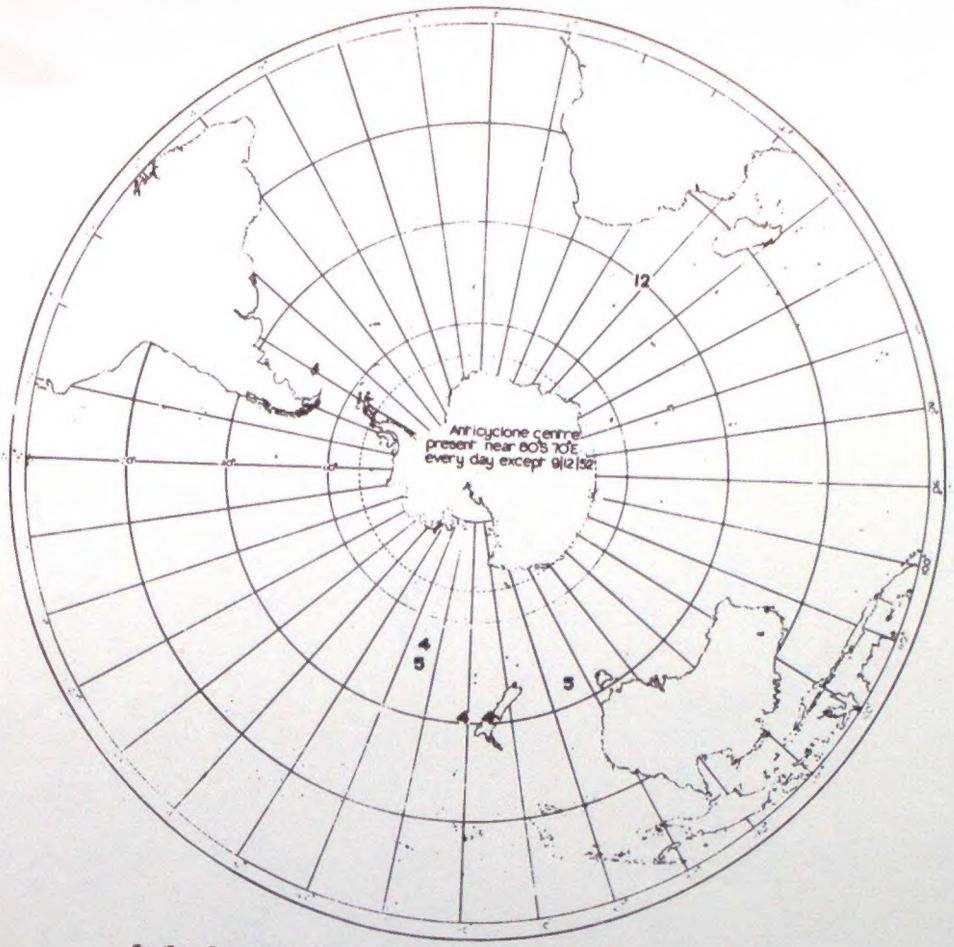


Fig 13a Occurrences of Quasi-Stationary Anticyclones South of 40°S Summer (DJF) 1952-3
Centres which stayed x days within 600 miles of the position marked by x. x plotted in all cases where x ≥ 4

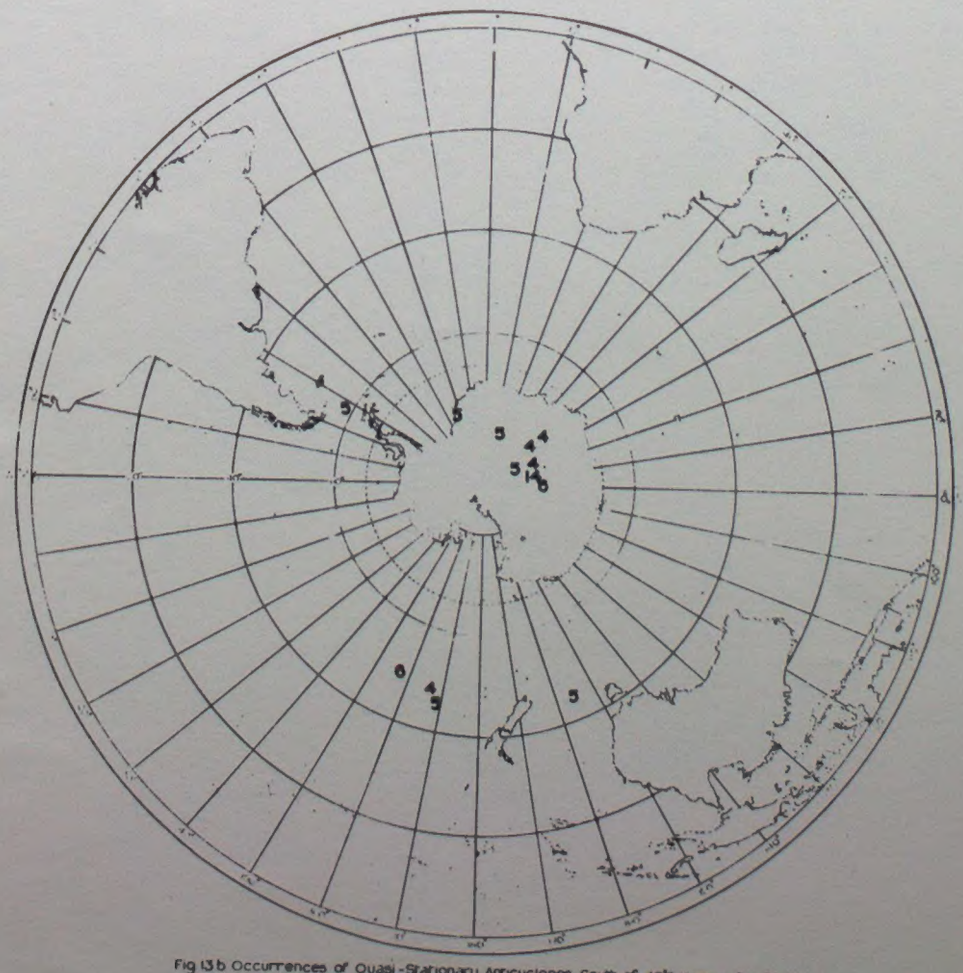


Fig 13b Occurrences of Quasi-Stationary Anticyclones South of 40°S Winter (JJA) 1952
Centres which stayed x days within 600 n miles of the position marked by x. x plotted in all cases where x ≥ 4

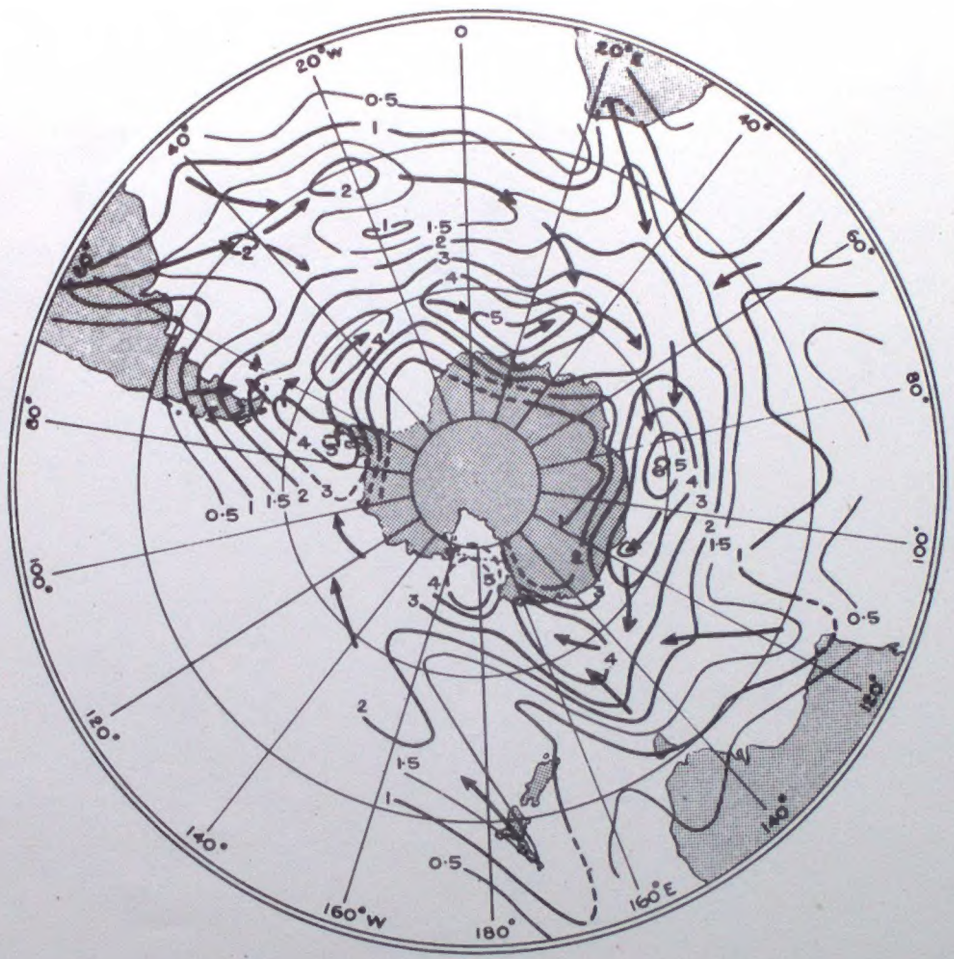


Fig. 14 Depression Frequencies: Jan.-Feb. 1947; mid March–mid April 1947, mid-March mid-April 1948.

Arrows indicate the general direction of movement.

(After Lamb and Britton)